VARIABLE FREQUENCY CHEVRON IN PRINTED MEDIA REFERENCE PATTERN TO IMPROVE SERVO DEMODULATION

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CLAIM OF PRIORITY

[0001] This application claims priority from U.S. Provisional Patent Application No. 60/460,205 entitled "Variable Frequency Chevron in Printed Media Reference Pattern to Improve Servo Demodulation" by Richard M. Ehrlich, filed April 2, 2003 incorporated herein by reference.

CROSS-REFERENCED CASES

[0002] The following applications are cross-referenced and incorporated herein by reference:

[0003] U.S. Provisional Patent Application No. 60/436,709 entitled "Systems for Multi-Pass Self-Servowriting," by Richard M. Ehrlich, filed December 27, 2002.

[0004] U.S. Provisional Patent Application No.60/436,712 entitled "Systems for Self-Servowriting Using Write-Current Variation," by Richard M. Ehrlich, filed December 27, 2002.

[0005] U.S. Provisional Patent Application No. 60/436,703 entitled "Methods for Self-Servowriting Using Write-Current Variation," by Rick Ehrlich, filed December 27, 2002.

[0006] U.S. Provisional Patent Application No. 60/436,673 entitled "Systems for Selective Multi-Pass Servowriting and Self-Servowriting," by Richard M. Ehrlich, filed December 27, 2002.

[0007] U.S. Provisional Patent Application No. 60/436,744 entitled "Systems Using Extended Servo Patterns with Multi-Pass Servowriting and Self-Servowriting," by Richard M. Ehrlich, filed December 27, 2002.

[0008] U.S. Patent Application No. 10/420,452 entitled "Systems for Multi-Pass Self-Servowriting," by Richard M. Ehrlich, filed April 22, 2003.

[0009] U.S. Patent Application No. 10/420,076 entitled "Systems for Self-Servowriting Using Write-Current Variation," by Richard M. Ehrlich, filed April 22,

2003.

[0010] U.S. Patent Application No. 10/420,498 entitled "Methods for Self-Servowriting Using Write-Current Variation," by Richard M. Ehrlich, filed April 22, 2003.

[0011] U.S. Patent Application No. 10/624,252 entitled "Systems for Conditional Servowriting," by Richard M. Ehrlich, filed April 22, 2003.

[0012] U.S. Patent Application No. 10/733,131 entitled "Methods to Determine Gross and Fine Positioning on a Reference Surface of a Media," by Richard M. Ehrlich et al., filed December 10, 2003.

FIELD OF THE INVENTION

[0013] The present invention relates to methods to servowrite media for use in data storage devices, and systems for applying such methods.

BACKGROUND

[0014] Advances in data storage technology have provided for ever-increasing storage capability in devices such as DVD-ROMs, optical drives, and disk drives. In hard disk drives, for example, the width of a written data track has decreased due in part to advances in read/write head technology, as well as in reading, writing, and positioning technologies. More narrow data tracks result in higher density drives, which is good for the consumer but creates new challenges for drive manufacturers. As the density of the data increases, the tolerance for error in the position of a drive component such as a read/write head decreases. As the position of such a head relative to a data track becomes more important, so too does the placement of information, such as servo data, that is used to determine the position of a head relative to a data track.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] Further details of embodiments of the present invention are explained with the help of the attached drawings in which:

[0016] **Figure 1** is a diagram showing components of a disc drive that can be used in accordance with embodiments of the present invention;

[0017] **Figure 2** is a diagram showing an example of a data and servo format for a disk in the drive of **Figure 1**;

[0018] **Figure 3** is a diagram showing servo information that can be written to the tracks shown in **Figure 2**;

[0019] **Figure 4** illustrates a portion of a reference pattern having a burst-region with variable frequency chevrons in accordance with one embodiment of the present invention; and

[0020] **Figure 5** illustrates a portion of a reference pattern having two sets of burst-regions with variable frequency chevrons in accordance with an alternative embodiment of the present invention.

DETAILED DESCRIPTION

[0021] Systems and methods in accordance with embodiments of the present invention can be used when servowriting, or self-servowriting, a rotatable storage medium in a data storage device, such as a hard disk drive. A hard disk drive can include at least one magnetic disk capable of storing information transferred through a read/write head. **Figure 1** is a schematic of an exemplary hard disk drive **100** for use with embodiments of the invention including at least one magnetic disk **102** and a read/write head **104** capable of storing information on at least one of the surfaces of the disk. The read/write head **104** is positioned over the surface of the disk by a closed-loop servo system that can be used to pivot a rotary actuator on which the head **104** is mounted or formed. The servo system can comprise a microprocessor **120** and a servo controller, the servo controller existing as circuitry within the hard disk drive **100** or as an algorithm resident in the microprocessor **120**, or as a combination thereof. In other embodiments, an independent servo controller can be used. The servo system uses positioning data read by the head **104** to determine the position of the head **104** over the disk **102**. When the servo system receives a command to position a head **104** over a track, the servo system determines an appropriate current to drive through a voice coil (not shown) of the rotary actuator **106** and commands a voice coil motor (VCM) driver **108** electrically connected with the voice coil to drive the current. A magnetic field produced by the current driven through the voice coil interacts with stationary magnets of a VCM, causing the actuator **106** to pivot.

[0022] The servo system can further include a spindle motor driver **122** to drive current through a spindle motor connected with the disk **102**, thereby rotating the disk **102**, and a disk controller **128** for receiving information from a host **122** and for controlling

multiple disk functions. The host **122** can be any device, apparatus, or system capable of utilizing the hard disk drive **100**, such as a personal computer or Web server. An interface controller can be included for communicating with the host **122**, or the interface controller can be included in the disk controller **128**. In other embodiments, the servo controller, VCM driver **108**, and spindle motor driver **112** can be integrated into a single application specific integrated circuit (ASIC). One of ordinary skill in the art can appreciate the different means for controlling the spindle motor and the VCM.

[0023] The disk controller **128** can provide user data to a read/write channel **114**, which can send data signals to a current amplifier or preamp **116** to be written to the disk(s) **102**. The disk controller **128** can receive servo and/or user data signals read by the read/write head **104** from the read/write channel **114**. The disk controller **128** can also send servo signals to the microprocessor **120**, or the disk controller **128** can control the VCM and spindle motor drivers directly. The disk controller **128** can include a memory controller (not shown) for interfacing with buffer memory **118**. In one embodiment, the buffer memory **118** can be dynamic random access memory (DRAM). The microprocessor **120** can include integrated memory (such as cache memory), or the microprocessor **120** can be electrically connected with external memory (for example, static random access memory (SRAM) **110** or alternatively DRAM).

[0024] The information stored on such a disk can be written in concentric tracks, extending from near the inner diameter (ID) of the disk to near the outer diameter (OD) of the disk **102**, as shown in the exemplary disk of **Figure 2**. In an embedded servo-type system, servo information can be written in servo wedges **230**, and can be recorded on tracks **232** that can also contain data. Data tracks written to the disk surface can be formatted in radial zones. Radial zones radiating outward from the ID can be written at progressively increased data frequencies to take advantage of an increase in linear velocity of the disk surface directly under a head in the respective radial zones. In a system where the actuator arm rotates about a pivot point such as a bearing, the servo wedges may not extend linearly from the ID to the OD, but may be curved slightly in order to adjust for the trajectory of the head as it sweeps across the disk.

[0025] **Figure 3** shows a portion of an exemplary final servo pattern within a servo wedge **230**. The final servo pattern includes information stored as regions of magnetization. As shown in **Figure 3**, where the at least one servo wedge **230** is longitudinally magnetized, grey blocks are magnetized to the left and white spaces are

magnetized to the right, or vice-versa. Alternatively, where the at least one servo wedge **230** is perpendicularly magnetized, grey blocks are magnetized up and white spaces are magnetized down, or vice-versa. In other embodiments, such as in optical data storage devices, information can be stored as indicia other than regions of magnetization. For example, the information can be stored as optical indicia. The final servo pattern is read by the head **104** as the surface of the spinning disk **102** passes under the head **104**. The servo pattern can include information identifying a data field and a position of the head relative to the data field. The information can include, for example, a servo address mark (SAM), track identification information, an index, etc. The exemplary final servo pattern illustrated in **Figure 3** is a simplification of a typical servo pattern. The servo information can be arranged in any order, and can include many more transition pairs than are illustrated (for example, the region containing track identification is truncated as shown, and commonly includes many more transition pairs than are illustrated). Further, additional information, such as partial or complete wedge number information, can be included in the final servo pattern. One of ordinary skill in the art can appreciate the myriad different arrangements of information that can be contained in a servo pattern. Systems and method in accordance with embodiments of the present invention should not be construed as being limited in scope to those examples provided herein.

[0026] Servo information often includes bursts of transitions called "servo bursts." The servo information can be positioned regularly about each track, such that when a data head reads the servo information, a relative position of the head can be determined that can be used by a servo processor to adjust the position of the head relative to the track. For each servo wedge, this relative position can be determined, in one example, as a function of the target location, a track number read from the servo wedge, and the amplitudes or phases of the bursts, or a subset of those bursts. The position of a head or element, such as a read/write head or element, relative to the center of a target track, will be referred to herein as a position-error signal (PES).

[0027] A centerline **334** for a given data track can be "defined" relative to a series of bursts, burst edges, or burst boundaries, such as a burst boundary defined by the lower edge of A-burst **336** and the upper edge of B-burst **338** in **Figure 3**. The centerline can also be defined by, or offset relative to, any function or combination of bursts or burst patterns. This can include, for example, a location at which the PES value is a maximum, a minimum, or a fraction or percentage thereof. Any location relative to a function of the

bursts can be selected to define track position. For example, if a read head evenly straddles an A-burst and a B-burst, or portions thereof, then servo demodulation circuitry in communication with the head can produce equal amplitude measurements for the two bursts, as the portion of the signal coming from the A-burst above the centerline is approximately equal in amplitude to the portion coming from the B-burst below the centerline. The resulting computed PES can be zero if the radial location defined by the A-burst/B-burst (A/B) combination, or A/B boundary, is the center of a data track, or a track centerline. In such an embodiment, the radial location at which the PES value is zero can be referred to as a null-point. Null-points can be used in each servo wedge to define a relative position of a track. If the head is too far towards the outer diameter of the disk, or above the centerline in **Figure 3**, then there will be a greater contribution from the A-burst that results in a more "negative" PES. Using the negative PES, the servo controller could direct the voice coil motor to move the head toward the inner diameter of the disk and closer to its desired position relative to the centerline. This can be done for each set of burst edges defining the shape of that track about the disk.

[0028] The PES scheme described above is one of many possible schemes for combining the track number read from a servo wedge and the phases or amplitudes of the servo bursts. For example, U.S. Pat. 5,381,281 to Shrinkle et al. describes a PES scheme including a quad-servo burst pattern in which the null-point is defined by a linear combination of the amplitudes of all four bursts, instead of simply the difference between two bursts as described immediately above. A quadrature-based track following algorithm applying a difference of sums of servo burst pair read voltages can minimize track following errors where servo bursts are mispositioned relative to one another. Such a scheme can benefit from embodiments of the present invention, as can many other track following schemes. One of ordinary skill in the art can appreciate the myriad different track following schemes for which embodiments of the present invention can be applied.

[0029] A disk drive can have tens of thousands of data tracks. A typical servo writing process can require, for example, 3.75 or more revolutions to complete steps for writing servo information for a data-track. If such a process requires on average roughly 4 revolutions to write each data-track, with 100,000 data-tracks and a spin-speed of 5400 RPM (90 Hz), for example, the process of writing servo wedges on each surface would take 4,444 seconds, or about 74 minutes. If the process is carried out on an expensive

servowriter, this can add substantially to the cost of the drive. Thus, drive manufacturers are motivated to use self-servowriting techniques to reduce or eliminate time spent servowriting data tracks using servowriters.

[0030] One such self-servowriting technique uses a media-writer to write servo patterns on a stack of disks. Each disk is then placed in a separate drive containing multiple blank disks. The drive can use the patterned disk as a reference to re-write servo patterns on all of the other disk surfaces in the drive, as well to write servo patterns on the reference surface, if desired. The media-writer can be an expensive instrument, and it may still take a very long time to write a reference pattern on the stack of disks. However, if a stack contains 10 blank disks, for example, then the media-writer can write the reference pattern for 10 drives in the time that it would have taken to servowrite a single drive. This scheme is a member of a class of self-servowriting techniques commonly known as "replication" self-servowriting.

[0031] Alternatively, a printed media disk can be placed in a drive containing multiple blank disks in substitution of (or in addition to) a media having a servo pattern written by a media-writer. Such a printed media disk can include a reference pattern transferred from a reticle or die. The reference pattern is a coarse pattern containing clocking and radial position information, providing a reference for writing final servo wedges on the disk surfaces. Printing a servo pattern on a media surface can reduce the time and expense required to write the servo pattern on the surface by transferring at least a portion of the reference pattern in one step or series of steps, rather than writing servo data on a track-by-track basis.

[0032] A magnetic printing station can be used to magnetically print or otherwise transfer the reference pattern using a known transfer technique. One such transfer technique is described in "Printed Media Technology for an Effective and Inexpensive Servo Track Writing of HDDs" by Ishida, et al. IEEE Transactions on Magnetics, Vol. 37, No. 4, July 2001. A blank disk (the reference surface) is DC erased along the circumferential direction of the disk by rotating a permanent magnet block on the disk surface. A template, or "master", disk is then aligned with the blank disk and the two disks are securely faced with each other by evacuating the air between the two disk surfaces through a center hole in the blank disk. An external DC field is applied again in the same manner as in the DC erasing process, but with an opposite polarity. Other techniques for transferring a reference pattern to a disk are well known, and are likewise

applicable to embodiments of the present invention.

[0033] Systems and methods in accordance with embodiments of the present invention can utilize variable frequency chevrons in a printed media reference pattern on a reference surface of a rotatable medium to improve servo demodulation. Although for simplicity a single printed media reference pattern will be described, it should be understood that there are many possible reference patterns that can utilize aspects of various embodiments of the present invention. In the exemplary reference pattern **440** shown partially in **Figure 4** and described herein, a preamble **442** includes a phase-lock-loop (PLL) and automatic gain control (AGC) region that can allow a drive system to lock up the PLL and AGC loops. The preamble as illustrated is truncated and simplified for purposes of explanation, and can include many more pairs of transitions. This region can be followed by a servo address mark (SAM). The time at which the SAM is encountered can give the demodulation circuitry a timing reference which can be used to accurately determine the location of the servo-bursts, to determine the time at which to begin looking for the next SAM, and to lock up a self-servo write (SSW) clock. In addition to the preamble and SAM regions, additional information can be included in a reference pattern. For example, the reference pattern can include an index-mark, or some other information identifying rotational position. In addition, the reference pattern can include information describing gross-radial position, such as a marker zone, as described in U.S. Pat. App. 10/733,131 entitled "Methods to Determine Gross and Fine Positioning on a Reference Surface of a Media". However, as shown in **Figure 4**, following the SAM are servo-bursts **444**. For printed media self-servo write (PM-SSW), the servo-bursts **444** in the reference pattern **440** can be pairs of oppositely-tilted chevrons, whose phase, relative to one another, can contain information about the radial position of a head, such as a read/write (R/W) head.

[0034] In an exemplary servo-demodulation scheme, such as those known to one of ordinary skill in the art, a digital servo demodulation circuit can digitize samples of the signal from the R/W head at a rate of 4 times per cycle of the servo-burst signal. Performing a discrete Fourier transform (DFT) of the signal (useful in determining the phase and/or magnitude of the bursts) can then involve multiplying signals by either 0, +1, or -1. That is, the circuitry need only add, subtract, or ignore samples to compute the DFT of a signal. In the printed media servo demodulation, it could be necessary to use such a low sample frequency to sample at 4 times per cycle of the signal that the front-end

analog circuitry would require larger capacitors than is practical in low-cost integrated circuits.

[0035] Systems and methods in accordance with one embodiment for printed media self-servowrite (specifically, servoing on a printed-media pattern) allow the analog-to-digital converter (A/D) to sample many more than 4 times per cycle of the signal. For example, an A/D can sample a filtered signal at 20 times per cycle. After conversion, the channel can filter the signal with a hard-coded narrow band filter, centered at the expected burst-frequency. The channel can then digitally filter and down-sample the signal, such as to 4 samples per cycle, and can demodulate the burst using the "normal" DFT circuitry. Filtering or treatment of reference patterns of differing density using signal process techniques is known in the art. For example, such a technique for processing lower density printed reference patterns is described in U.S. Pat. 6,704,156 to Baker et al.

[0036] System and methods can take advantage of a "20X" factor by "down sampling" a signal over the chevrons by a factor of 5, producing 4 samples per cycle. A DFT can then be performed for each of the chevrons. For a part of the stroke, such as near the ID of the reference surface in ID region, this pattern can be used. At some distance toward the OD, the burst-frequency can be switched to a frequency higher than the original frequency. For example, if the servo burst frequency used near the ID were 6 MHz (a 6 MHz cycle-rate for the signal, with the channel sampling at 20X the cycle-rate, or 120 MHz), then the reference pattern can switch to a 9 MHz burst-frequency at mid-stroke. If the frequency at or near the ID is limited to 6 MHz by the minimum allowable feature dimension, then near mid-stroke (where the radius of a track can be about 1.5 times the radius at the ID), a 9 MHz burst frequency can be supported. The preamble, SAM, and any other digital information can be maintained at the original 6 MHz rate, in at least certain systems and methods. Maintaining this information at the low frequency can allow the channel to lock up its PLL and detect the SAM using a single frequency independent of the location of the R/W head. Once the R/W head passes over the burst-region where the higher-frequency bursts should be encountered, the system can "up-sample" the digitized signal, such that the resulting pseudo-samples can occur at 20X the new cycle frequency. It should be noted that in other embodiments, the A/D can sample at different rates. For example, the A/D can sample a filtered signal at 16 times per cycle.

[0037] For the example of a 1.5X frequency (new to original burst cycle frequency), the drive system can interpolate as follows. If the original stream of samples is denoted as x_k (k is the index of the sample), 3 samples of y_k can be produced for every 2 samples of x_k received:

$$y_{3K} = 3 * x_{2K}$$

$$y_{(3K+1)} = x_{2K} + 2 * x_{(2K+1)}$$

$$y_{(3K+2)} = 2 * x_{(2K+1)} + x_{(2K+2)}$$

The resultant signal can then be passed through the same hard-coded band-pass filter used for the 6 MHz bursts, down-sampled, and a DFT taken as before.

[0038] In systems and methods in accordance with another embodiment, the hard-coded band-pass filter can be re-designed to deal with the 1.5X frequency signal as the "normal" frequency. Interpolation can be applied to make the reference pattern work with a burst-frequency that is only 2/3 of the new "normal" frequency. In such an embodiment, if the input signal is still denoted as x_k and the output signal as w_k:

$$w_{2K} = 2 * x_{3K}$$

$$w_{(2K+1)} = x_{(3K+1)} + x_{(3K+2)}$$

This "down-sampled" signal processing can be used for the 6 MHz signal, and "normal" processing can be used for the 9 MHz signal. In the previous embodiment, "normal" signal processing can be used for the 6 MHz bursts, with "up-sampling" for the 9Mhz bursts.

[0039] Signal processing techniques can be further be applied, for example, on an alternative reference pattern wherein chevrons near the ID are a lower frequency than digital information preceding the chevrons. Such a reference pattern can be useful, for example, where it is desired that the digital information be printed having a minimum feature size. An angle of a chevron requires that the chevron have a smaller feature width than a width of digital information preceding the chevron so that the width

encountered by the R/W head - the product of the feature width and the sine of the chevron angle - is equivalent to the feature width of the digital information. Thus, the chevron limits the feature width of the digital information. However, if the chevron is printed (or servowritten) at a lower frequency and down-sampled (or the digital information is up-sampled), the digital information can be printed (or servowritten) having the minimum feature width. Optionally, the chevron pattern can be printed or servowritten at the higher frequency at some position along the stroke where the feature width is no longer a limiting factor.

[0040] Reference patterns can include higher frequency bursts that occupy no more space than previously occupied by the lower frequency bursts, but that allow more burst cycles in each wedge. Such an implementation can have the advantage of using a higher frequency signal (with a resulting lower position error signal (PES) noise), but can suffer a problem such as having a radial location where the burst frequency suddenly changes. Such a problem can be dealt with in any of a number of ways. In a first approach to dealing with such a problem, the drive system can simply deal with the fact that demodulation of the signal when the head straddles the two regions (of high frequency and low frequency bursts) may not be acceptable, or may be otherwise less than optimal. The drive system can keep careful track of the location of that region, and have the servo expect "bad" burst-demodulation there. Since the eccentricity of the disk can be as much as 100 microns or so, only two samples of a track may have the possibility of placing the head in such a "straddle" position. This can be due to the printed-media pattern moving in and out sinusoidally at the spin-speed, with the R/W head being held at a relatively constant radius to servowrite final wedges on a drive. If the decision is made to "spare-out" (i.e., mark as unusable) all of the affected tracks, it would represent about 400 data-tracks (at 100 KTPI, or 100000 tracks-per-inch; a typical track-density for drives in the near future). That might be 1% or so of the tracks in a 2.5-inch disk drive. That would be a high, but not unacceptable, penalty.

[0041] In an alternative approach, two sets of burst-regions can be used for every wedge, as shown in **Figure 5**. Near the ID (region **A**), both sets **444,546** can be low-frequency. Near the OD (region **C**), both sets **444,546** can be high frequency. In a middle, transition region **B**, which can be relatively narrow - such as on the order of, or slightly wider than, the maximum eccentricity of 100 microns - one set can contain low-frequency bursts and the other can contain high-frequency bursts. In the transition

region **B**, either the low-frequency or the high-frequency bursts can be used. If writing is started at the OD, the high-frequency bursts (in both sets **444,546**) can be used from the OD until near (but before) the start of the transition-region **B**. There, the drive system can switch to using the high-frequency bursts **444**, or one of the two sets. Near (but before) the end of the transition region **B**, the drive can switch to using low-frequency bursts **546**, or one of the two sets. Finally, once the head is "comfortably" beyond the transition region **B**, the drive system can use low-frequency bursts in both sets **444,546**. It would be possible to suffer degraded PES noise, and thus degraded tracking, wherever only one set of bursts is being used. If the degradation is sufficiently poor, the drive system can "spare out" the affected tracks, as was possible for the first approach above. It may be more beneficial, however, to compensate for degraded PES noise using techniques such as multi-pass servowriting, additional WORF revolutions and/or conditional-servowriting. In multi-pass servowriting, additional passes allow patterns such as servo burst pairs to be written and/or trimmed on separate passes. The additional passes reduce the written runout, as the average misplacement decreases when the number of passes increases. Each burst in a servo pattern can also be written and/or trimmed in multiple passes. As PES noise degrades, more time can be spent burst trimming/writing, or in collection of WORF data. In conditional-servowriting, extra revolutions can be used to allow writing of servo digital and/or burst data only when the demodulated PES is within certain limits. Any subset of these techniques (or all of them) might be used to trade a higher time-penalty (in terms of revolutions spent per servo track written) for a written-in runout that is similar to that achieved over the rest of the drive's stroke, even though the PES noise is degraded, relative to what could be obtained with all of the bursts.

[0042] The example described herein uses two burst frequencies, with a factor of 3/2 difference in the frequencies. It should be understood that the invention can be extended to any number of different frequencies, such as may increase roughly in proportion with increasing radius of the disk, at the possible cost of more complexity in the "up-sampling" or "down-sampling" circuitry necessary, and in issues related to dealing with switches between frequencies. For example, where the frequency is doubled, a simplified interpolation scheme is required, or where the frequency is quintupled for every three samples, a more complicated interpolation scheme is required. At any one boundary between burst-frequencies, though, the servo can only be required to deal with two frequencies, namely the two on either side of the boundary. Further, the particular

method of up-sampling and/or down-sampling the signal (using linear interpolation) is not the only possible method, as is apparent to one of skill in the art.

[0043] The foregoing description of preferred embodiments of the present invention has been provided for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise forms disclosed. Many modifications and variations will be apparent to one of ordinary skill in the relevant arts. The embodiments were chosen and described in order to best explain the principles of the invention and its practical application, thereby enabling others skilled in the art to understand the invention for various embodiments and with various modifications that are suited to the particular use contemplated. It is intended that the scope of the invention be defined by the claims and their equivalence.